Model-dependent and independent implications of the first Sudbury Neutrino Observatory results

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Abstract

We briefly discuss some implications of the first solar ν results from the Sudbury Neutrino Observatory (SNO) experiment in the charged-current channel. We first show that the present SNO response function is very similar to the Super-Kamiokande (SK) one above 8.6 MeV in kinetic electron energy. On the basis of such equivalence we confirm, in a completely model-independent way, the SNO evidence for an active, non-electron neutrino component in the SK event sample, with a significance greater than 3σ. Then, by assuming no oscillations into sterile neutrinos, we combine the SK+SNO data to derive allowed regions for two free parameters: (i) the ratio f_B of the *true* ^{8}B ν flux from the Sun to the corresponding value predicted by the standard solar model (SSM), and (ii) the ν_e survival probability $\langle P_{ee}\rangle$, averaged over the common SK and SNO response function. We obtain the separate 3σ ranges: $f_B = 1.03^{+0.50}_{-0.58}$ (in agreement with the SSM central value, $f_B = 1$) and $\langle P_{ee}\rangle = 0.34^{+0.61}_{-0.18}$ (in $> 3\sigma$ disagreement with the standard electroweak model prediction, $\langle P_{ee}\rangle = 1$), with strong anticorrelation between the two parameters. Finally, by taking f_B and its uncertainties as predicted by the SSM, we perform an updated analysis of the 2ν active neutrino oscillation parameters $(\delta m^2, \tan^2\omega)$ including all the solar ν data, as well as the spectral data from the CHOOZ reactor experiment. We find that only the solutions at $\tan^2\omega \sim O(1)$ survive at the 3σ level in the global fit, with a preference for the one at high δm^2—the so-called large mixing angle solution.

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I. INTRODUCTION

The Sudbury Neutrino Observatory (SNO) experiment [1] has recently presented the first measurements of the $\nu_e + d \to p + n + e^-$ reaction rate induced by ^{8}B solar neutrinos through charged currents (CC) [2] . The observed CC event rate, normalized to the latest standard solar model (SSM) prediction [3],

$$\mathrm{SNO/SSM} = 0.347 \pm 0.029 \ , \tag{1}$$

not only confirms the deficit of solar neutrino events previously observed by the chlorine [4], gallium [5], and water-Cherenkov [6,7] experiments, but provides a $> 3\sigma$ evidence [2] for a $\nu_{\mu,\tau}$ contribution in the Super-Kamiokande (SK) measurement of the $\nu_x + e^- \to \nu_x + e^-$ reaction rate ($x = e, \mu, \tau$) in a similar energy range [7],

$$\mathrm{SK/SSM} = 0.459 \pm 0.017 \ . \tag{2}$$

The SK-SNO comparison can be made rigorously model-independent by making an appropriate choice for the SK energy threshold, as suggested in [8,9] and discussed also in the SNO paper [2]. In this work we first provide (Sec. II) an improved discussion of such model-independent comparison, which, based on the (previously undisclosed) detailed SNO detector specifications, confirms the $> 3\sigma$ evidence for a $\nu_{\mu,\tau}$ flavor component in the SK event sample. We then assume (Sec. III) no oscillations into sterile neutrinos, and derive combined constraints on two free parameters: (i) the ratio f_B of the *true* ^{8}B ν flux from the Sun to the corresponding value predicted by the SSM, and (ii) the ν_e survival probability $\langle P_{ee} \rangle$ averaged over the SK-SNO response function. Such constraints confirm the SSM prediction for f_B, and strongly indicate an average ν_e flux suppression of about one third ($\langle P_{ee} \rangle \sim 1/3$). Finally (Sec. IV) we assume the validity of the SSM, and perform and updated analysis of all the available solar neutrino data (including the SNO event rate) in a 2ν active oscillation framework. Large mixing angle solutions are clearly preferred in the global fit, while the small-mixing one is not allowed at the 3σ level (99.73% C.L.) by the parameter estimation test. We conclude our work in Sec. V.

II. USING THE SK-SNO EQUIVALENCE (WITH NO ADDITIONAL ASSUMPTION)

An important characteristic of any solar neutrino experiment is the energy spectrum of parent neutrinos contributing to the collected event sample in the absence of oscillations—the so-called response function $\varrho(E_\nu)$ [10]. The response function basically folds the solar neutrino energy spectrum with both the differential interaction cross section and with the detector threshold and energy resolution, and thus it takes different forms for each experiment. However, it can be made (partly accidentally) equal in SK and SNO by an appropriate choice of the detected electron energy thresholds (or, more generally, energy ranges), as shown in [8,9] on the basis of the *expected* SNO technical specifications.

By repeating the analysis in [8] with the present SNO kinetic energy threshold ($T_e^{\mathrm{SNO}} \geq$ 6.75 MeV) and energy resolution [2], we find a best-fit SK-SNO agreement for a SK threshold

$T_e^{\rm SK} \geq 8.6$ MeV (instead of $T_e^{\rm SK} > 5$ MeV $- m_e$, for which the value in Eq. (2) is officially quoted [7]). Such "adjusted" threshold is in good agreement with the one estimated in the SNO paper ($T_e^{\rm SK} \geq 8.5$ MeV [2]). Figure 1 displays our calculations for the corresponding SK and SNO response functions to ^{8}B neutrinos, which appear to be in very good agreement with each other. Concerning the small shape difference in the first half of the response functions, we estimate that, in our analysis, the corresponding effect is (in the worst case) a factor of five smaller than the effect of the total SNO uncertainty in Eq. (1), so that we can safely take $\varrho_{\rm SK} = \varrho_{\rm SNO}$. With the adjusted SK threshold, the SK and SNO detectors are thus equally sensitive to the incoming ^{8}B neutrinos. The possible small contribution of *hep* neutrinos (not shown in Fig. 1) does not spoil the SK-SNO equalization of response functions [9], as far as the *hep* flux is taken below the experimental upper limit provide by the latest SK spectral measurements [7].

Although there is no official number quoted yet by the SK collaboration for the SK/SSM value at $T_e^{\rm SK} \geq 8.6$ MeV, one can try to recover it from the published SK spectral data [7,11]. We adopt the provisional SNO own estimate [2], corresponding to take

$$\mathrm{SK/SSM} = 0.451 \pm 0.017 \ \ (T_e^{\rm SK} \geq 8.6 \text{ MeV}) \ , \tag{3}$$

which amounts to a small shift in the central value of the total SK rate. The attached SK error is assumed to be basically the same as in Eq. (2), since it should be dominated by systematic errors rather than by statistical uncertainties. Furthermore, the SK-SNO comparison is dominated by the (presently) larger SNO uncertainties, so that any (presumably small) official SK re-evaluation of the numbers in Eq. (3) is not expected to produce significant changes in the results discussed below [12].

For $\varrho_{\rm SK} = \varrho_{\rm SNO}$, the following relations hold *exactly* [8,9]:

$$\mathrm{SNO/SSM} = f_B \langle P_{ee} \rangle \ , \tag{4}$$

$$\mathrm{SK/SSM} = f_B \langle P_{ee} \rangle + f_B \frac{\sigma_a}{\sigma_e} \langle P_{ea} \rangle \ , \tag{5}$$

where f_B is the ratio between the true (unknown) ^{8}B ν_e flux at the Sun and its SSM prediction [3], $\langle P_{ee} \rangle$ is the ν_e survival probability (energy-averaged over the common SK-SNO response function), $\langle P_{ea} \rangle$ is the averaged transition probability to active neutrinos ($\nu_a = \nu_{\mu,\tau}$), and σ_a/σ_e is the ratio of the (properly averaged [8,9]) cross sections of ν_a and ν_e on electrons. We calculate $\sigma_a/\sigma_e = 0.152$ for $T_e^{\rm SK} \geq 8.6$ MeV. Notice that the above relations do not imply any assumption either on f_B, or on possible sterile neutrino oscillations, or on the functional form of $P_{ee}(E_\nu)$ or $P_{ea}(E_\nu)$, and thus they are *completely model-independent.*

From the above relations one can derive that:

$$\mathrm{SK/SSM} < \mathrm{SNO/SSM} \quad \text{is always forbidden } (\langle P_{\mu\tau} \rangle < 0) \ , \tag{6}$$

$$\mathrm{SK/SSM} = \mathrm{SNO/SSM} \quad \text{is allowed only if } \langle P_{\mu\tau} \rangle = 0 \ , \tag{7}$$

$$\mathrm{SK/SSM} > \mathrm{SNO/SSM} \quad \text{is allowed only if } \langle P_{\mu\tau} \rangle > 0 \ . \tag{8}$$

Figure 2 displays the above constraints at a glance. The SK+SNO experimental data are well within the region where there *must* be $\nu_e \to \nu_{\mu,\tau}$ transitions, independently of a possibly open [13] $\nu_e \to \nu_s$ channel. Only at $> 3\sigma$ (more precisely, at 3.1 sigma) the experimental

data would hit the diagonal line which parametrizes the case of no $\nu_e \to \nu_{\mu,\tau}$ transitions (corresponding to either no oscillations or pure $\nu_e \to \nu_s$ oscillations). Such results represent an alternative way to look at the SNO evidence [2] for a $\nu_{\mu,\tau}$ component in the SK events at $> 3\sigma$.

III. USING THE SK-SNO EQUIVALENCE (WITHOUT STERILE NEUTRINOS)

The SNO results [1] and the model-independent analysis in the previous section show that there is evidence for active neutrino transitions. Therefore, it is legitimate to explore the consequences of the *additional* hypothesis of *purely active* flavor transitions, corresponding to take $\langle P_{ea}\rangle = 1 - \langle P_{ee}\rangle$. In such a case, the SK-SNO relations in Eqs. (4) and (5) read

$$\mathrm{SNO/SSM} = f_B \langle P_{ee}\rangle \ , \tag{9}$$

$$\mathrm{SK/SSM} = f_B \langle P_{ee}\rangle + f_B \frac{\sigma_a}{\sigma_e}(1 - \langle P_{ee}\rangle) \ , \tag{10}$$

providing a system of two equations in the two unknowns f_B and $\langle P_{ee}\rangle$. By fitting the experimental values of SNO/SSM and SK/SSM given in Eqs (1) and (3), respectively, one can then determined allowed ranges for f_B and $\langle P_{ee}\rangle$.

Figure 3 shows the contours of the allowed region in the $(\langle P_{ee}\rangle, f_B)$ plane for $\chi^2 = \Delta\chi^2 = 1, 4$, and 9, whose *projections* onto the coordinate axes give the 1σ, 2σ, and 3σ separate ranges [14] for f_B and $\langle P_{ee}\rangle$. The strong anticorrelation reflects the fact that a high ^{8}B flux can be partly compensated by a smaller survival probability, and vice versa. The projected 3σ range for f_B ($f_B = 1.03^{+0.50}_{-0.58}$) is in agreement with the SSM prediction (shown with its $\pm 1\sigma$ error band from [3], $f_B = 1^{+0.20}_{-0.16}$). On the other hand, the projected 3σ range for the average survival probability ($\langle P_{ee}\rangle = 0.34^{+0.61}_{-0.18}$), clashes with the standard electroweak model prediction of electron flavor conservation ($\langle P_{ee}\rangle = 1$) at $> 3\sigma$. In the context of this figure, the standard model of the Sun appears to be in better shape that the standard model of electroweak interactions.

The results indicate that, in the case of generic active oscillations (i.e., no other assumption apart from $\langle P_{es}\rangle = 0$ in the range probed jointly by SK and SNO), the ν_e survival probability takes basically the lowest value allowed by pre-SNO experiments. It has been shown in [15] that the lowest values of $\langle P_{ee}\rangle$ (in the ^{8}B energy range) are typically reached within the so-called large mixing angle (LMA) solution to the solar neutrino problem, which may therefore be expected as favored. This will be confirmed by the analysis in the next section.

IV. USING ALL THE SOLAR NEUTRINO DATA (ASSUMING THE SSM AND TWO-FAMILY ACTIVE OSCILLATIONS)

From the SNO results [2] and from the analysis in the previous Sections we have learned that: (i) There is evidence for active neutrino oscillations, and (ii) Assuming purely active ν oscillations, the SSM is confirmed and the ν_e survival probability should be $\sim 1/3$ in the SK-SNO energy range. Let us now make two further assumptions about neutrino physics,

namely, that the ν fluxes from the Sun can be taken as predicted (with their uncertainties) by the SSM [3], and that active neutrino oscillations occur in an effective two-family framework. The latter hypothesis is totally correct if the mixing angle θ_{13} vanishes, and is accurate up to $O(\sin^2\theta_{13})$ corrections if $\theta_{13} > 0$. We remind that the joint analyses of SK atmospheric neutrino data [16] and of the CHOOZ reactor results [17] place stringent upper limits on θ_{13} [18–20]. Moreover, the CHOOZ data forbid large ν_e disappearance for neutrino square mass differences higher than $\sim 0.7 \times 10^{-3}$ eV^2, and thus they are also relevant to cut away the region of energy-averaged solar neutrino oscillations [20–22]. Therefore, we perform a 2ν analysis by adding the final CHOOZ spectral results [17] (14 bin, as discussed in [22]) to the usual solar neutrino data, and show then the results in the mass-mixing plane $(\delta m^2, \tan^2\omega)$, covering both octants in $\omega = \theta_{12}$ [23]. Since we are now assuming a specific functional form for $P_{ee}(E_\nu)$ (i.e., the one predicted by standard oscillation theory at any given mass-mixing point), the SK-SNO model-independent comparison becomes unimportant, and we can use the full SK rate given in Eq. (2) [7].

Concerning SNO, in this work we include the total CC rate [Eq. (1)] but not the published CC energy spectrum [2]. Notice that the present SNO spectrum information should be subdominant as compared to SK since, although one expects a SNO sensitivity to spectral deviations a factor of two larger than in SK [24], the current SNO spectral errors (both statistical and systematic) are more than a factor of two larger than in SK (and the published SNO event sample is an order of magnitude smaller than the SK one). Moreover, it is not easy to recover (from both the published SNO and SK data) the information needed to propagate *jointly*, on both the SK and SNO spectra, the correlated ^{8}B shape spectrum uncertainties [25] around the best-fit ν spectrum (that we take from [26] as in [7]). Therefore, we prefer to postpone the SNO spectrum analysis (and its properly correlated combination with the SK spectrum) to a future work [27]. The total SNO CC rate is, however, already important by itself, and to appreciate its impact we show first the 2ν analysis *without* SNO for reference.

Figure 4 shows the results of the 2ν analysis using the three pre-SNO total solar neutrino rates (chlorine [4], combined gallium [5], SK [7]) and to the 14-bin CHOOZ data [17] (relevant to suppress the likelihood of the high-δm^2 region), as derived by drawing iso-$\Delta\chi^2$ contours (for $N_{\rm DF} = 2$) around the global χ^2 minimum. The fit in Fig. 4 favors the small-mixing angle (SMA) solution, as compared to the regions at $\tan^2\omega \sim O(1)$, usually referred to as large-mixing angle at high δm^2 (LMA) and at low δm^2 (LOW), extending down to the quasivacuum and vacuum oscillation (QVO and VO) regions. Figure 5 shows the impact of the SK day-night spectral data [7,11] (19+19 bins minus one adjustable normalization factor), that cut away the vacuum solutions and also change the relative likelihood of the local SMA, LMA, and LOW best fits, favoring the LMA solution (see also Table I). Notice also the small region allowed at 99.73% C.L. in the lowest δm^2 decade (the so-called Just-So^2 solution, see the first of Ref. [15] and references therein). Similar results have been largely discussed in the recent solar neutrino literature (see, e.g., [15,11,28,29]), and we do not add further comments here.

Figure 6 is analogous to Fig. 4, but including the SNO CC rate [2]. The LMA (SMA) solution in Fig. 6 is enlarged (reduced) as compared to Fig. 4, due to the anticipated SNO preference for relatively small values of the ν_e average survival probability, which tend to favor the LMA case. The SMA solution tends to adapt to the low value $\langle P_{ee}\rangle \sim 1/3$ by privileging its rightmost part (where the nonadiabatic ν_e suppression is stronger), and indeed

the final compromise makes the SMA local fit comparable to the LMA one (see Table I). However, in doing so, the SMA fit also privileges the part where spectral deviations are sizable, contrary to the SK day-night spectrum observations.

Indeed, the SMA solution disappears at $> 3\sigma$ when the SK day-night spectral data are included, as shown in Fig. 7 (analogous to Fig. 5, but including the SNO total CC rate). The "tension" between the total rate information (pushing the SMA to the right) and the SK spectrum (pushing the SMA to the left), which was already emerging from the latest SK data analysis [11], is now sufficiently strong to produce a significant decrease of the likelihood of the SMA solution. Since the SNO spectral data [2] (not included here) do not show any deviation from the standard shape within the (now large) errors, we may expect that the addition of such data in future analyses can only corroborate such trend. The LMA solution appears to be favored in the global fit, enhancing the hopes of interesting new physics at KamLand [30] and at future neutrino factories [31]. The LOW solution turns out to be slightly less favored then the LMA one, essentially because the gallium data prefer an increase of the ν_e survival probability at low energies, which is more easily provided in the LMA region rather than in the LOW solution (see, e.g., [15]). However, the LOW solution is still in good shape, and should be tested through day-night earth matter effects in the BOREXINO experiment [32] or, with less sensitivity, through winter-summer matter effects after several years of data taking in the Gallium Neutrino Observatory (GNO) [33]. Notice that the LOW solution extends down to the quasivacuum oscillation [34] region, which might be probed in BOREXINO by pushing its time-variation sensitivity close to its upper limits [35]. Notice that no VO or Just-So^2 solutions survive in Fig. 7. Finally, we remark that the indications for a relatively small value of $\langle P_{ee}\rangle$ suggest that a large, unmistakable neutral-to-current ratio enhancement (roughly $\propto 1/\langle P_{ee}\rangle$) should be found by the SNO experiment in its second phase of operation (neutral current mode).

V. CONCLUSIONS

We have discussed the following implications of the first SNO results (with increasing degree of model dependence): (i) Evidence for $\nu_e \to \nu_{\mu,\tau}$ transitions from a model-independent comparison of SK and SNO; (ii) Bounds on the ^{8}B neutrino flux factor f_B and on the average ν_e survival probability under the hypothesis of (generic) active ν oscillations; and finally (iii) Marked preference for large-mixing solutions *vs* the small mixing one, by assuming both active oscillations and standard solar model predictions. It seems that the SNO experiment has just started to delight us with the first of a series of interesting results.

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TABLES

TABLE I. 2ν active oscillations: Positions and local values for the relevant χ^2 minima (SMA, LMA, LOW, and Q(VO) solutions). Upper part: pre-SNO situation, without and with SK day-night spectral data [7] (19+19 bin). Lower part: post-SNO situation (total SNO CC rate included [2], 1 datum). In all cases, the fit includes the chlorine [4], combined gallium [5] and SK [7] total rates (3 data), as well as the final CHOOZ spectral data [17] (14 bin).

	$\log_{10}(\tan^2\omega)$	$\log_{10}(\delta m^2/\mathrm{eV}^2)$	χ^2	$\log_{10}(\tan^2\omega)$	$\log_{10}(\delta m^2/\mathrm{eV}^2)$	χ^2
	Data: pre-SNO rates + CHOOZ			Data: pre-SNO rates + SK spec. + CHOOZ		
SMA	-3.03	-5.04	7.70	-3.40	-5.10	49.3
LMA	-0.54	-4.56	10.6	-0.48	-4.31	42.2
LOW	-0.14	-7.00	15.6	-0.12	-6.99	46.8
(Q)VO	± 0.25	-10.0	7.80	$+0.39$	-9.34	48.1
	Data: post-SNO rates + CHOOZ			Data: post-SNO rates + SK spec. + CHOOZ		
SMA	-2.94	-5.00	12.0	-3.50	-5.10	57.7
LMA	-0.35	-4.36	11.7	-0.43	-4.31	43.0
LOW	-0.20	-6.99	16.4	-0.17	-6.97	47.5
(Q)VO	± 0.53	-10.1	10.5	$+0.31$	-9.32	49.0

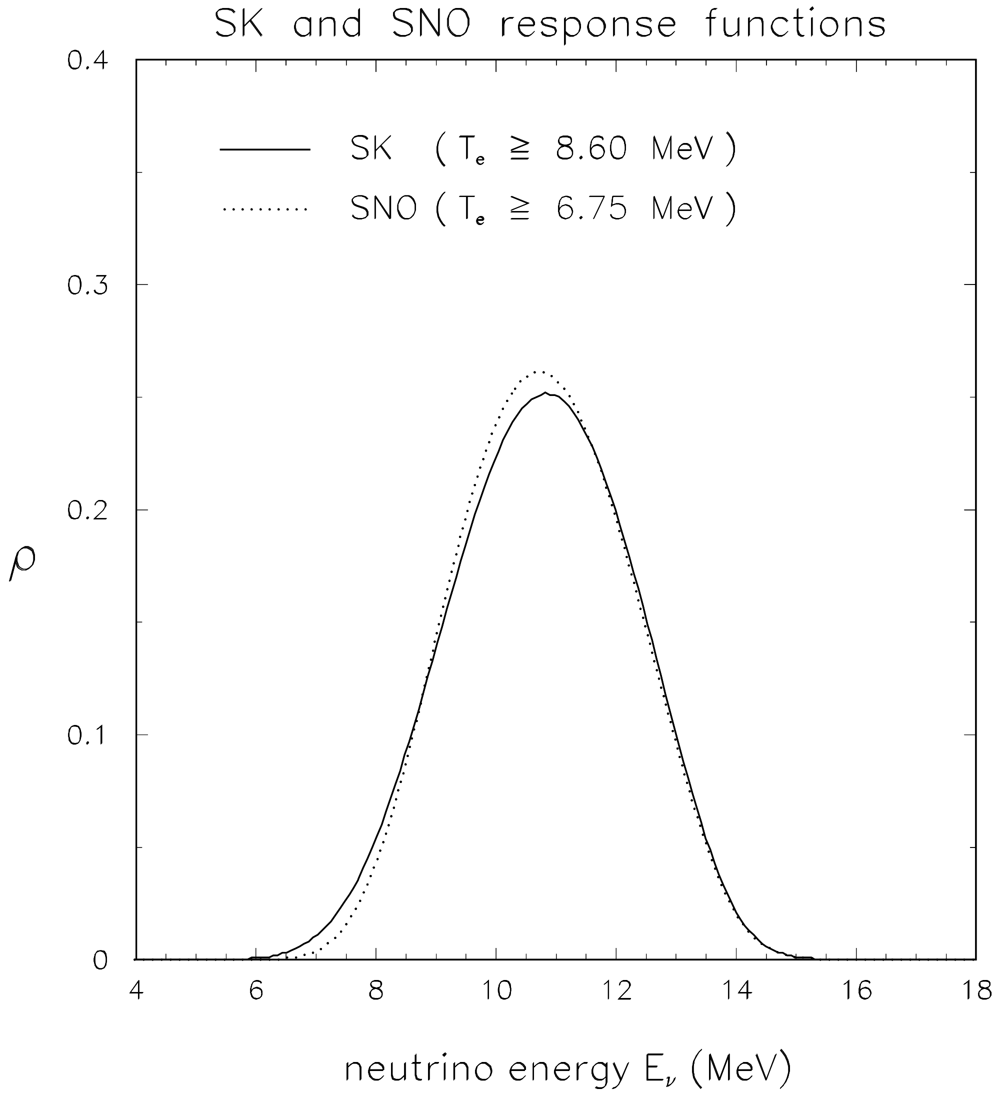

Fig. 1. Best-fit equalization of the SK and SNO response functions to ^{8}B neutrinos, as obtained by shifting the SK threshold to 8.6 MeV in electron kinetic energy.

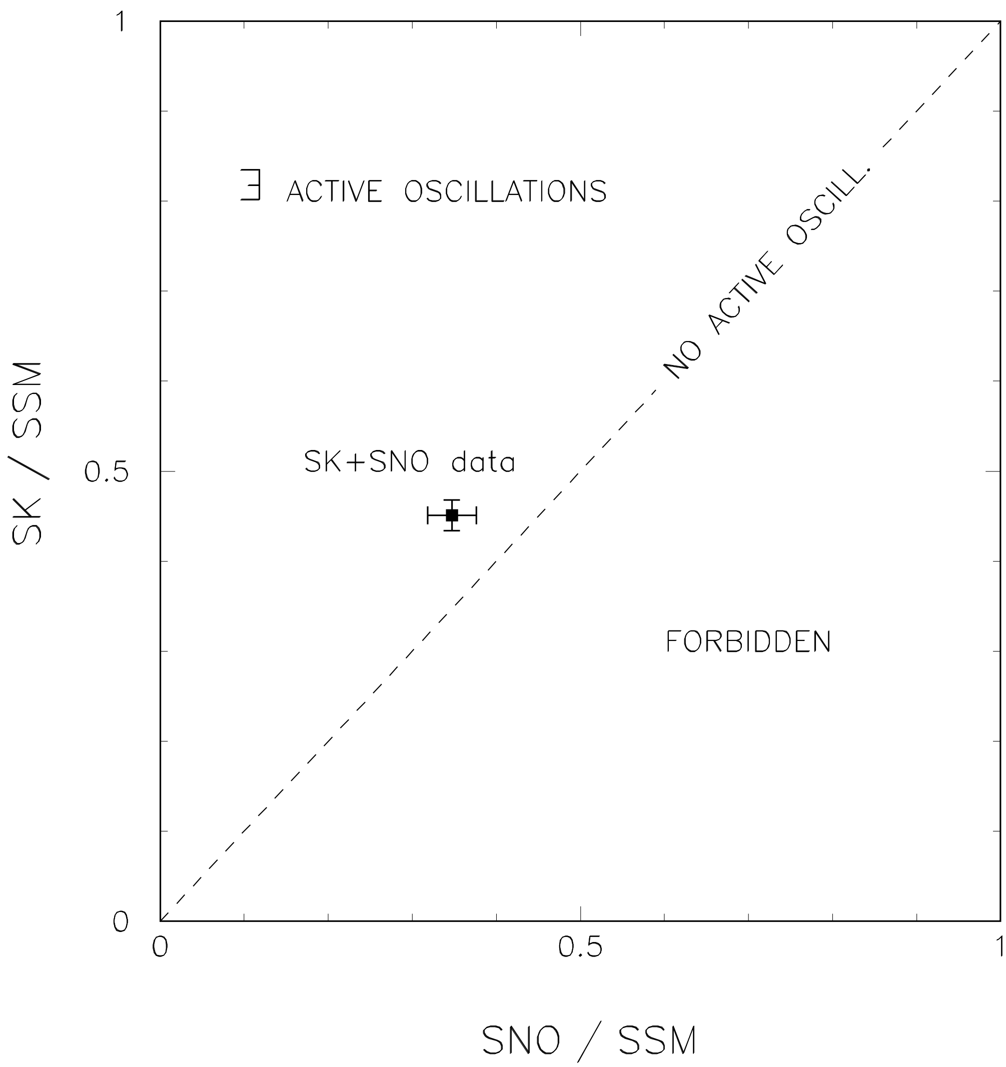

Fig. 2. Model-independent consequences of the SK and SNO results with equalized response functions: The data are well within the region where active neutrino transitions $\nu_e \to \nu_{\mu,\tau}$ *must* occur, and are 3.1σ distant from the diagonal line of “no active oscillations”. This conclusion does not depend on either the standard solar model or the possible presence of additional transitions to sterile neutrinos. See the text for details.

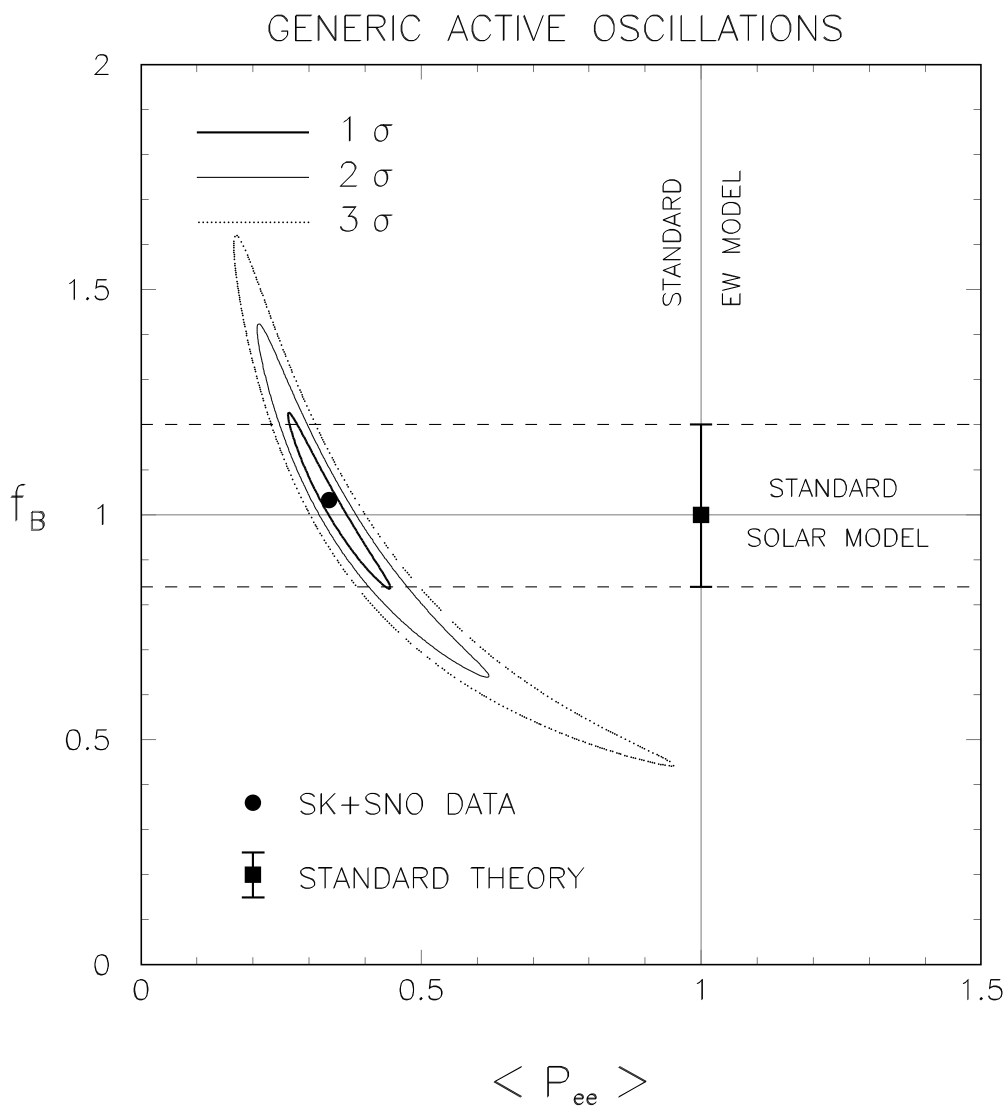

Fig. 3. Model-independent analysis of SK and SNO, assuming no oscillations into sterile states, in the plane charted by f_B (free factor multiplying the SSM ^{8}B neutrino flux) and $\langle P_{ee} \rangle$ (ν_e survival probability averaged over the SK-SNO response function). The contours of the allowed region (obtained for $\Delta\chi^2 = 1$, 4, and 9) give, after projections onto the axes ($N_{\mathrm{DF}} = 1$), the separate 1σ, 2σ, and 3σ ranges for f_B and $\langle P_{ee} \rangle$. The f_B range is in good agreement with the SSM predictions [3] (shown as a $\pm 1\sigma$ horizontal band), while the $\langle P_{ee} \rangle$ range is in $> 3\sigma$ disagreement with the standard electroweak model prediction of electron flavor conservation ($\langle P_{ee} \rangle = 1$).

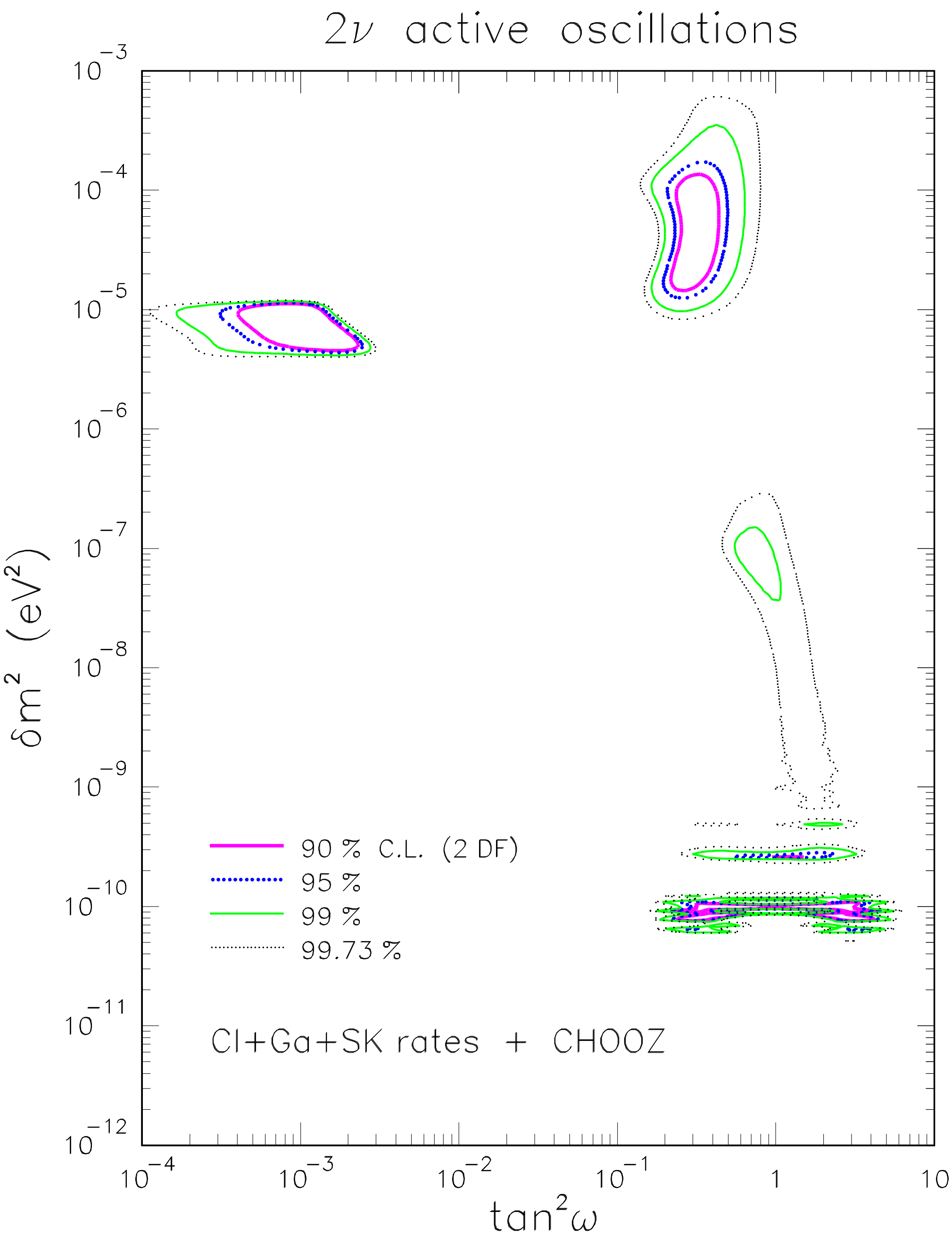

Fig. 4. Pre-SNO 2ν oscillation analysis of total neutrino event rates. CHOOZ data included. The regions shown in the figure are allowed 90, 95, 99, and 99.73% C.L. for the joint two-parameter estimation test [14], as obtained by drawing iso-χ^2 contours at $\Delta\chi^2 = 4.61$, 5.99, 9.21, and 11.83 above the global minimum.

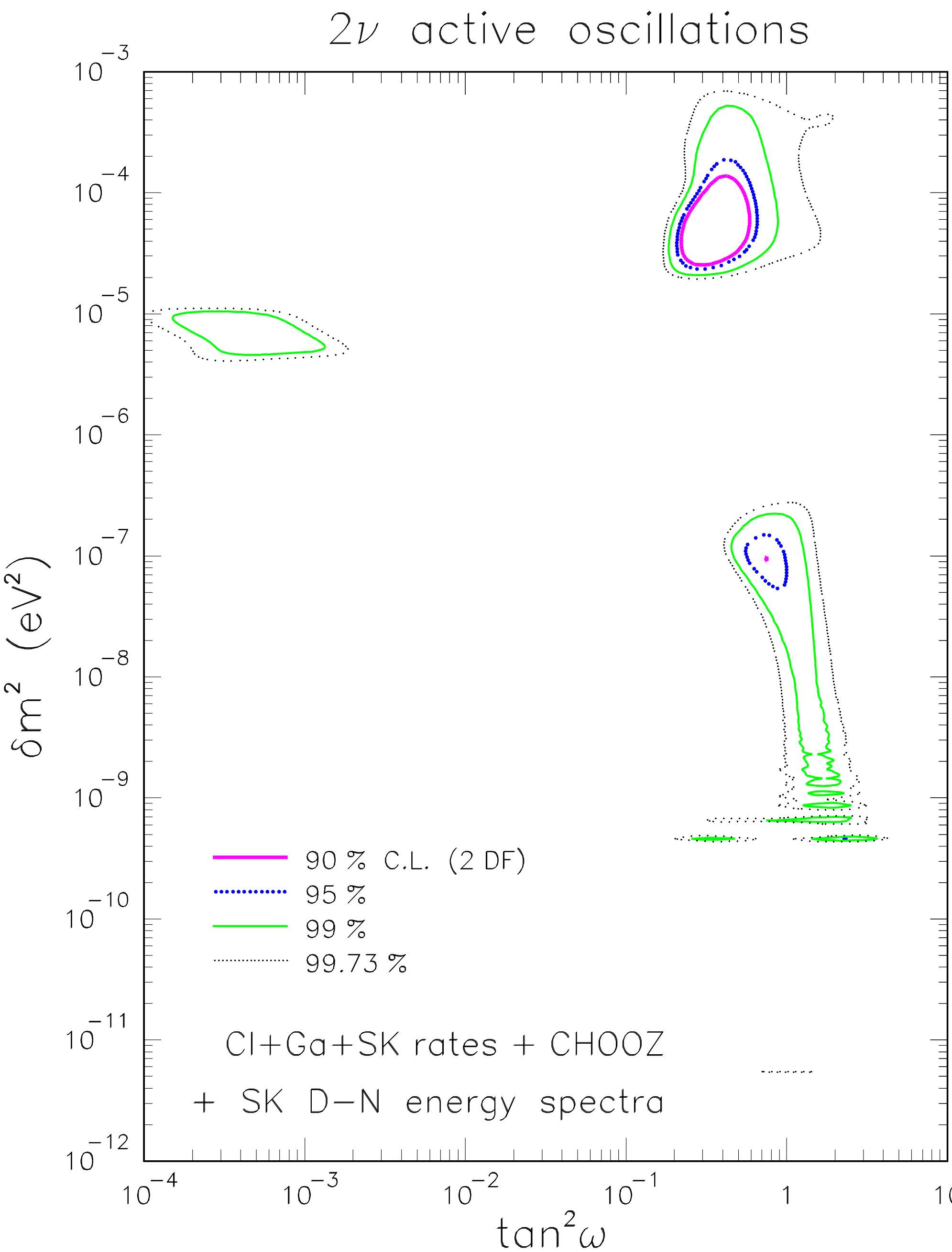

Fig. 5. Pre-SNO 2ν oscillation analysis of total neutrino event rates and of SK day-night energy spectra. CHOOZ data included.

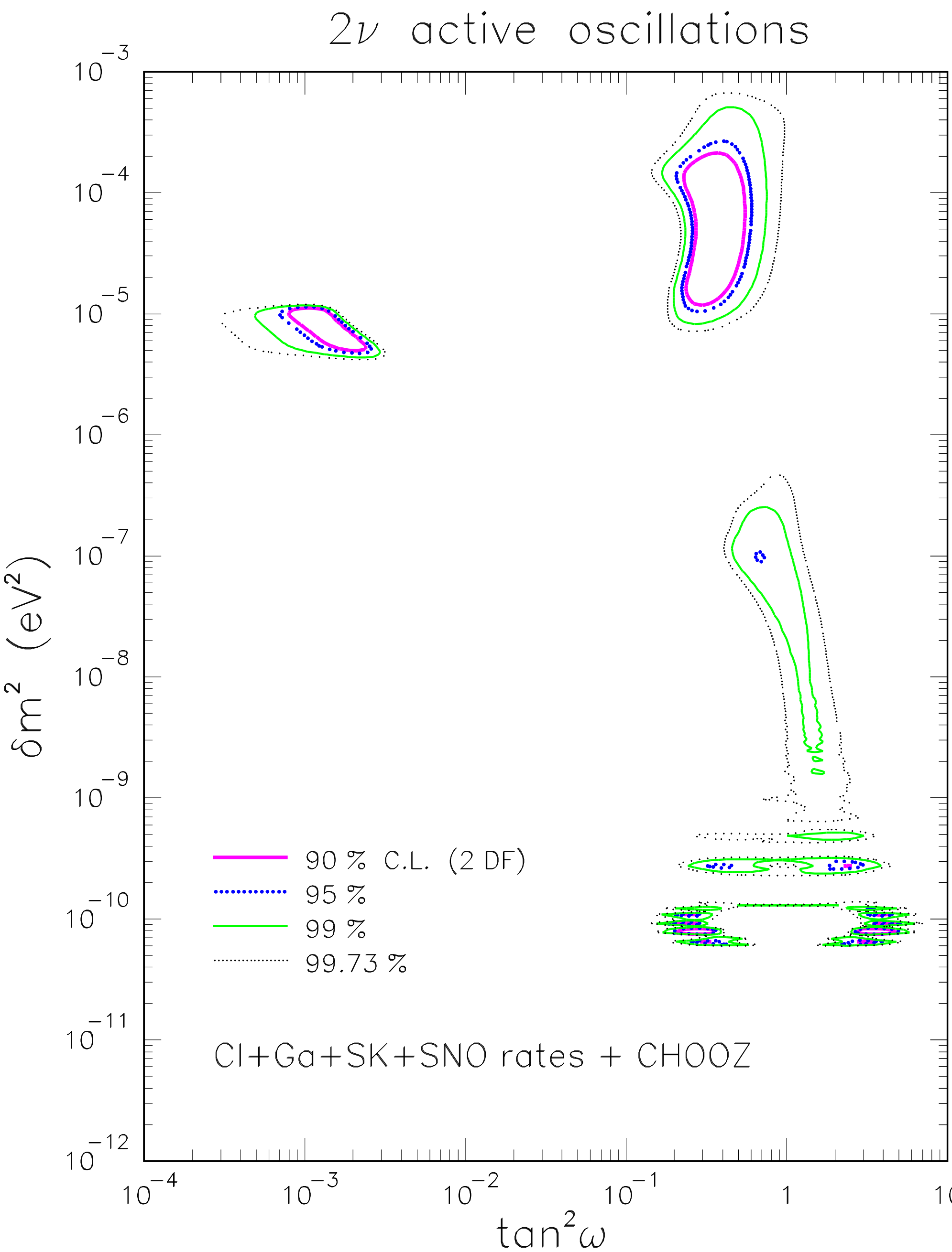

Fig. 6. Post-SNO 2ν oscillation analysis of total neutrino event rates. CHOOZ data included.

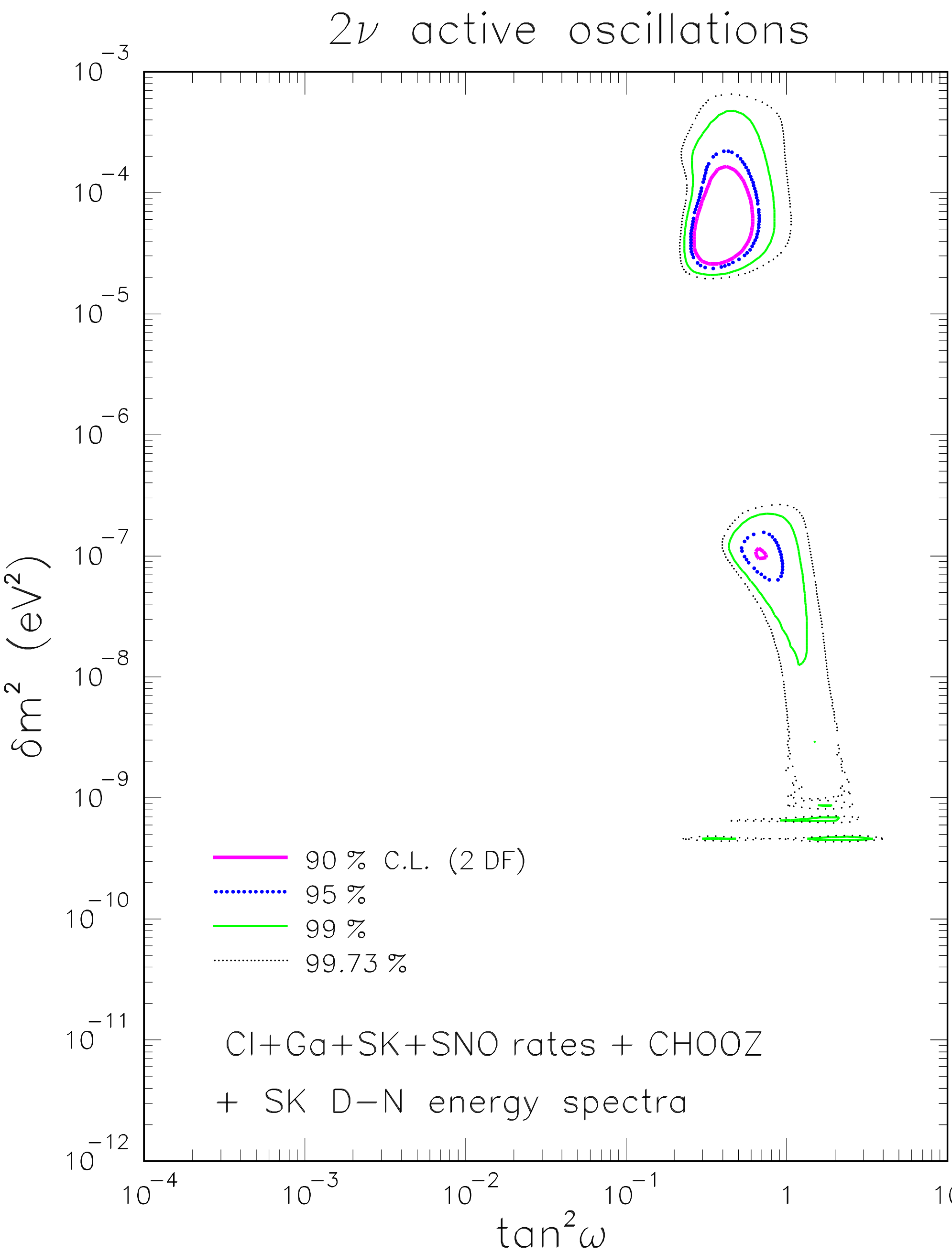

Fig. 7. Post-SNO 2ν oscillation analysis of total neutrino event rates and of SK day-night energy spectra. CHOOZ data included. Solutions at small mixing are highly disfavored. See the text for details.